Electro-Optic Imaging Fourier Transform Spectrometer

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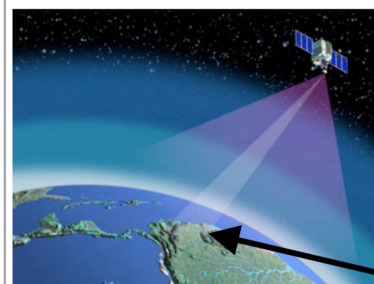
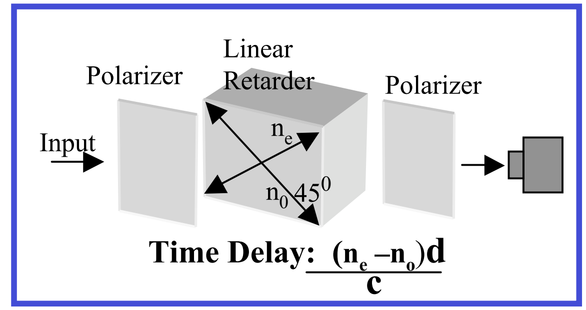
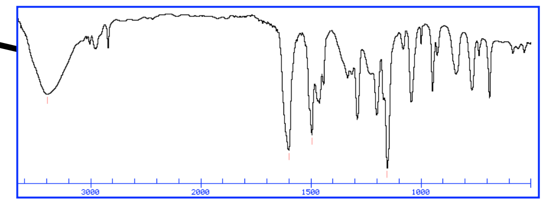
Description and Objectives

The objective of this tasks to develop and demonstrate an innovative compact, low mass, Electro-Optic Imaging Fourier Transform Spectrometer (E-O IFTS) with no moving parts. The spectral region of this spectrometer will be 1 – 2.5 μm (1000 – 4000 cm^{-1}) to allow high-resolution, high-speed measurement of a large number of different atmospheric gases simultaneously in the same airmass. This E-O IFTS consists of an imaging optics; a series of cascaded birefringent elements sandwiched between a series of liquid crystal based electro-optic switches; and a broadband IR photodetector array







Plans

Design comprehensive system architecture of an Electro-Optic Imaging Fourier Transform Spectrometer (E-O IFTS) in the 1-2.5 micron consisting of) High birefringence polymer retarders; 2) dichoric polarizers operational in IR spectral region; 3) Liquid Crystal material suitable IR band phase switching; 4) IR imaging camera

- Build a 2-stage feasibility E-O FTS breadboard

Develop multiple-stage E-OIFTS breadboard and perform spectral data capture experimental studies

Schedule and Deliverables

Year 1:

- 3-stage E-O FTS breadboard at 1-2.5 μm (1000 – 4000 cm^{-1}) .

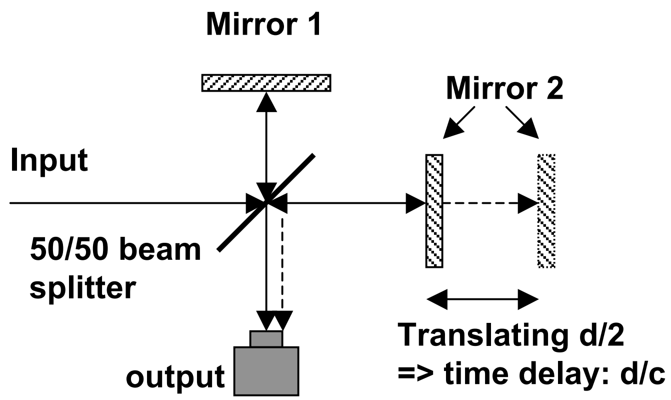
Year 2:

- Multi-stage E-OIFTS breadboard with resolution < 1cm^{-1}

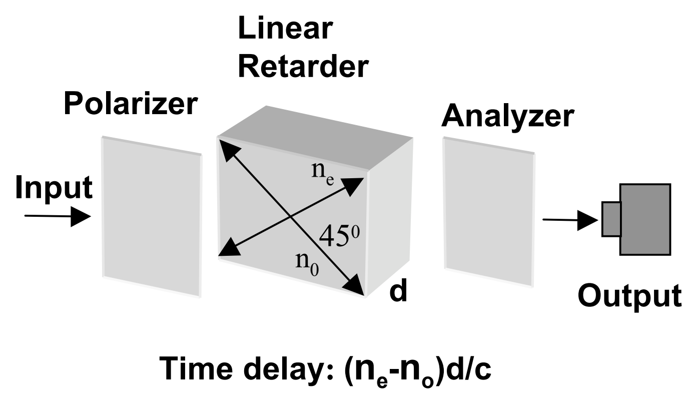
•Year 3:

- Integrated E-OIFTS breadboard system (with I/O and spectral data recovery post-processing) and laboratory demonstration

E-O FTS Concept



A) Michelson interferometer based FTS



B) E-O based FTS

- In a Michelson interferometer based FTS, a beam splitter splits an input beam into two equal-amplitude components; after a time delay introduced by moving one of the mirrors, they meet and interfere with each other.

- In an E-O based FTS, a polarizer splits an incident beam into two orthogonally polarized beam components; they propagate at different velocities (phase delay) inside a retarder; then an analyzer forces them to interfere with each other.

Principle of Fourier Transform Spectrometer

By smoothly translating one mirror, the optical path difference [OPD] $x = 2L$ (where x is *twice* the distance L traveled by the translating mirror) between the beams reflecting off the two mirrors is varied continuously, producing an interferogram $I(x)$, an example of which is illustrated above. A derivation of the specific intensity $I_k(x)$ observed for radiation of a single wavenumber k gives

$$I_k(x) = J(k)\,\langle T(k)\rangle\,\tfrac{1}{2}[1+\cos(kx)] \qquad (1)$$

(e.g., Vanasse and Sakai 1967, Schnopper and Thompson 1974), where $J(k)$ is the incident intensity and $\langle T(k)\rangle$ is the beamsplitter transmission function (averaged over polarizations and combined, in practice, with the efficiency of the subsequent optics).

The total intensity measured for a given OPD x from radiation at all wavenumbers is found by integrating (1), which is equivalent applying an inverse Fourier cosine transform $\mathcal{F}_c^{-1}$,

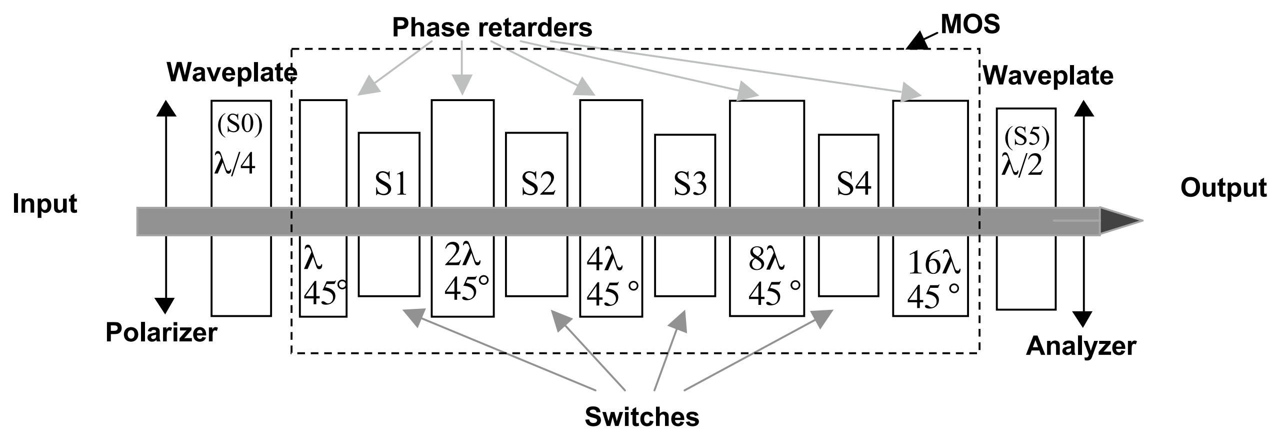
$$\begin{aligned}
I(x) &\equiv \int_0^\infty I_k(x)\,dk = \frac{1}{2}\int_0^\infty [1+\cos(kx)]\,\langle T(k)\rangle\,J(k)\,dk \\
&= \frac{1}{2}\int_0^\infty \langle T(k)\rangle\,J(k)\,dk + \frac{1}{2}\int_0^\infty \cos(kx)\,\langle T(k)\rangle\,J(k)\,dk \\
&= \tfrac{1}{2}I(0) + \frac{1}{2}\int_0^\infty \cos(kx)\,\langle T(k)\rangle\,J(k)\,dk \\
&= \tfrac{1}{2}I(0) + \tfrac{1}{2}\mathcal{F}_c{}^{-1}[\langle T(k)\rangle\,J(k)].
\end{aligned} \qquad (2)$$

In (2), the fact that the intensity of the white light fringe ($x = 0$) can be written

$$I(0) = \int_0^\infty I_k(0)\,dk = \int_0^\infty \langle T(k)\rangle\,J(k)\,dk, \qquad (3)$$

$$\langle T(k)\rangle\,J(k) = 2\mathcal{F}_c[I(x) - \tfrac{1}{2}I(0)].$$

E-O FTS Working Principle



- By adding a quarter-wave plate and a half-wave plate switches, the E-O FTS directly extracts (in quarter-wave steps) the autocorrelation of an incoming signal at the time delay established by the MOS unit.
- Series of time (phase) delay are established by electrically switching (aligning) N-stages of 45^{o}-oriented phase retarders (Γ_i=1λ, 2λ, 4λ, ..., $2^N\lambda$).
- After obtaining autocorrelation, spectrum is recovered by performing straight forward Fourier transformation:

  Power density spectrum $\xleftrightarrow{\text{FT pairs}}$ Auto correlation

Application of EOIFTS

- Operating in solar occultation mode, the E-O FTIR spectrometer would cover the 1 to 2.5 micron region (10000 - 4000 cm^{-1}) with high signal-to-noise ratio and spectral resolution (0.25 cm^{-1}).
  - Many atmospheric gases have their strongest absorption bands in the 1 to 2.5 micron region. These include NO, NO_2, CO_2, CO, OCS, N_2O, HNO_3, and N_2O_5, (e.g. CO_2 at 2.05 & 1.58 microns) providing many opportunities for interesting science. For example, all the principle components of atmospheric NOx ($NO+NO_2$) and NOy ($NOx+HNO_3+2.N_2O_5+ClNO_3$) can be measured in this spectral region.
  - These species are the major cause of stratospheric ozone destruction and require careful monitoring to gauge their response to climate change and changing amounts of stratospheric chlorine.

Primary Advantages of an EOIFTS

Limitations of a conventional mechanical IFTS

- Over the course of a 5-year mission, tens of millions of strokes will be required, making wear or fatigue a serious risk
- The moving optical element cannot be rigidly held, making it sensitive to vibration and requiring that it be "caged" during launch to prevent damage, adding risk (failure of the caging mechanism to reopen).
- Accelerating and decelerating the optical elements can torque the spacecraft, making it difficult to maintain accurate pointing.

Advantages of an EOIFTS

- A high-resolution FTIR spectrometer without moving parts therefore represents a substantial improvement in reliability, mission duration, and performance.
- Two orders of magnitude smaller in size and mass.

System Parameters Comparisons EOIFTS VS. GIFTS*

Instrument	GIFTS	EOIFTS	Comments
Size (m)	0.8x0.4x0.4	0.2x 0.1x 0.1	
Mass (kg)	100	4	
Average Power (W)	55	5	Orbit Average
Resolution (cm^{-1})	0.34	0.67	
Bandpass (cm^{-1})	685 - 1130 1650 - 2250	4000 - 10000	* To be demonstrated In the proposed work
Detectors	HgCdTe and InSb	QWIP	
Scan Repetition Rate (s)	1.2	0.5	per spectrum

*** GIFTS: Geosynchronous Imaging Fourier transform Spectrometer**

Spectrum Recover Algorithm

- Power density spectrum $S(\omega) \xleftrightarrow{\text{FT pairs}}$ Auto correlation P:

$$S(\omega) = \frac{1}{\Delta\omega}\left[P_0 + 2\sum_{m=1}^{\infty} P_m^A \cos(\frac{2\pi m\omega}{\Delta\omega}) + 2\sum_{m=1}^{\infty} P_m^B \sin(\frac{2\pi m\omega}{\Delta\omega})\right]$$

- Auto correlation P is sampled in four quarter-wave steps (0, π, π/2, and –π/2):

$$P_m^0 = \frac{1}{2}\int_0^\infty S(\omega)d\omega + \frac{1}{2}\int_0^\infty S(\omega)\cos(\frac{2\pi m\omega}{\Delta\omega})d\omega$$

$$P_m^\pi = \frac{1}{2}\int_0^\infty S(\omega)d\omega - \frac{1}{2}\int_0^\infty S(\omega)\cos(\frac{2\pi m\omega}{\Delta\omega})d\omega$$

==> cosine component coeff.: $P^A_m = P^0_m - P^\pi_m$,

$$P_m^{\frac{\pi}{2}} = \frac{1}{2}\int_0^\infty S(\omega)d\omega + \frac{1}{2}\int_0^\infty S(\omega)\sin(\frac{2\pi m\omega}{\Delta\omega})d\omega$$

$$P_m^{\frac{-\pi}{2}} = \frac{1}{2}\int_0^\infty S(\omega)d\omega - \frac{1}{2}\int_0^\infty S(\omega)\sin(\frac{2\pi m\omega}{\Delta\omega})d\omega$$

==> sine component coeff.: $P^B_m = P_m^{\pi/2} - P_m^{-\pi/2}$

zero-order components: $P_0 = P^0_m + P^\pi_m = P_m^{\pi/2} + P_m^{-\pi/2}$

Spectral Resolution

Similar to a conventional FTS, the spectral resolution,
EO-FTS is related to the maximum optical path difference, ? x? or
equivalently, the maximum time delay, ? max, between the two interfering
waves: $? ? ? \frac{1}{? x_{max}} ? \frac{1}{d ?(n_o ? n_e)?} ? \frac{1}{? ?2^N}$? If a total of N switches (N stages)

is used, the time delay of each switch will be approximately $2^0?$, $2^1?$,..., $2^N?$
with maximum time delay $?_{max} \sim 2^N ?_{med}$ where $?_{med}$? is the central
r the proposed spectrum range of
1.0 ~ 2.5 ? m, the central wavelength is about 1.8 ? m (5500 cm^{-1}). Thus the
spectral resolution for an 11 -stages and a 13 -stages EO -FTS will be about
2.68cm^{-1} (~ 1 nm) and 0.67cm^{-1} (~ .25 nm) respectively.

Phase Switch Scheme for a 4-stage E-O FTS

Obtain Cosine components :

- By aligning λ/4 wave plate to 0°
- Rotate λ/2 wave plate (0° or 45°) so the output of two beams are either in parallel with even number of switches (including S5) aligned at 45° or in perpendicular with odd number of switches (including S5) aligned at 45°
- Each retarder experiences all its subsequent switch operations (i.e., S1~S4 for 1λ, S2~S4 for 2λ, S3~S4 for 4λ, S4for 8λ, and none for 16λ):
  - A retarder with an even number of switches at 0° following it ==>the retardance will be added on the total delay; otherwise, subtracted.
  - The last retarder always add to the total delay.
- Subtraction of the two sets of data with the polarization status in parallel or perpendicular gives the cosine components of the Fourier transformation, while the addition gives the zero-order.

Phase Switch Scheme for a 4-stage E-O FTS

- ## Cosine components :

  Pol.:polarization status: '||' for parallel, '+' for perpendicular between two beam components.

  S1 ~S4, switches, λ/2: λ/2 waveplate,

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Phase Switch Scheme for a 4-stage E-O FTS

Obtain Sine components :

- By aligning $\lambda/4$ wave plate to 45°
- Rotate $\lambda/2$ wave plate (S5) so the output of two beams are either in parallel (if it is at at 45°) or in perpendicular (if it is at 0°)
  - Switches S1~S4 all add a π phase shift to MOS output ==> Even number of switches does not affect the orientation of MOS overall.
  - The polarization status between two components depends only on $\lambda/2$ wave plate (S5):
- As in cosine case, each retarder experiences all its subsequent switch operations (i.e., S1~S4 for 1λ, S2~S4 for 2λ, S3~S4 for 4λ, S4for 8λ, and none for 16λ):
  - A retarder with an even number of switches at 0° following it ==>the retardance will be added on the total delay; otherwise, subtracted.
  - The last retarder always add to the total delay.
- Subtraction of the two sets of data with the polarization status in parallel or perpendicular gives the sine components of the Fourier transformation, while the addition gives the zero-order.

Phase Switch Scheme for a 4-stage E-O FTS

- **Sine components :**

  Pol.:polarization status: '||' for parallel, '+' for perpendicular between two beam components.

  S1 ~S5, switches, S5: λ/2 waveplate.

	S2S3S4/2Retardance				1λ45454504516-8-4-2-1=1||204545		
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	S2S3S4/2Retardance				λ4545450016-8-4-2-1=1+		0454
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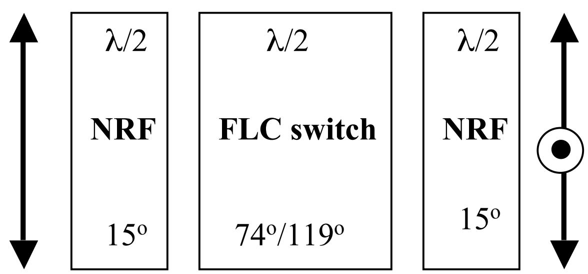
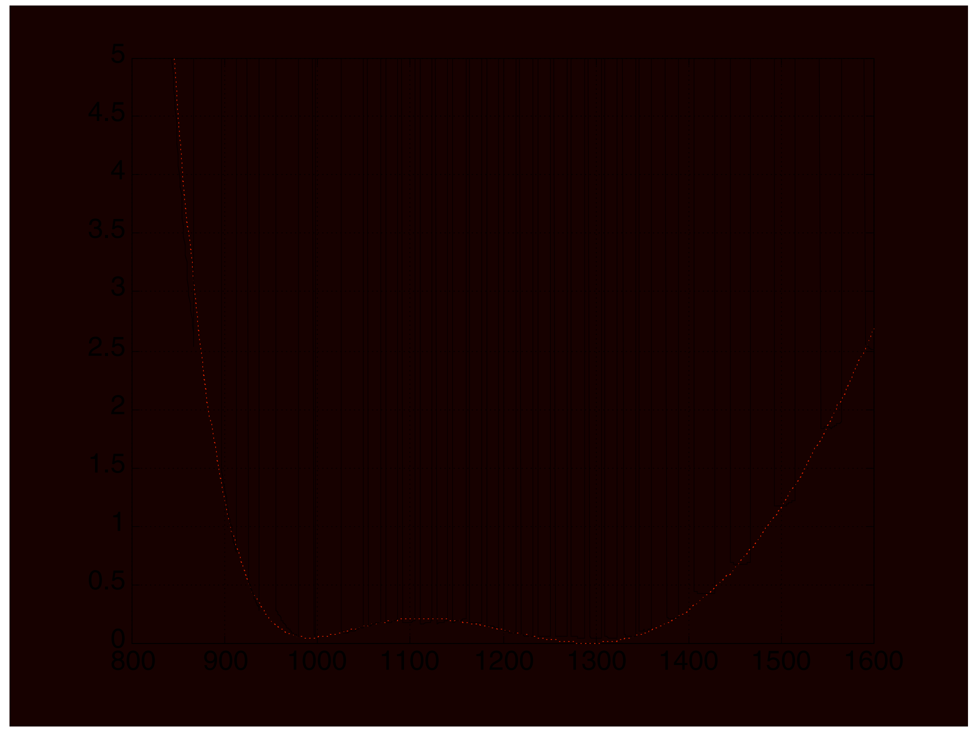
Fabrication and Testing of Achromatic Switches

- Made of two passive Nitto Denko retardation film (NRF) sheets and one FLC switch
- Switches operated at speed of 100μs with driving voltage <5v; covers spectrum range 0.93~1.43μm

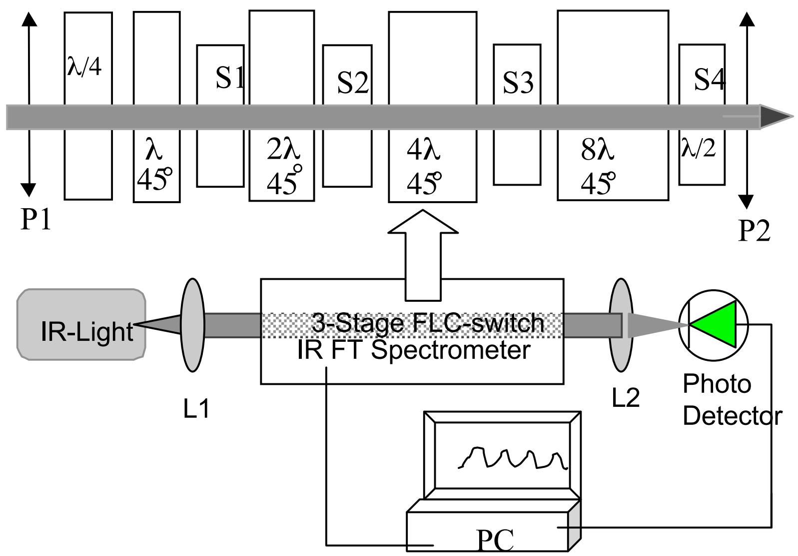


Schematic of an achromatic switch



Typical test result (red: simulation)

FY'03 Accomplishment
- Integration of a 3-stage Module



Schematic of the 3-stage spectrometer test system

Photo of Lab setup for the 3-stage spectrometer.

- Testing with 3-stage Module

- LC devices are switched in a “complementary sequence”
- Cosine and sine components of the FT spectrum are obtained with the $\lambda/4$ retarder aligned to 0^o or 45^o respectively.
- Recover spectrum from collected data using developed algorithm

- Testing Procedure of the 3-stage Module (Continued)

Phase Switch Scheme for obtaining Cosine components :

- By aligning $\lambda/4$ wave plate to 0°
- Rotate $\lambda/2$ wave plate S4 (to 0° or 45°) so the output of two beams are either of 0 phase shift (with even number of switches aligned at 45°) or of π phase shift (with odd number of switches aligned at 45°)
- Each retarder experiences all its subsequent switch operations except switch S4 (i.e., S1~S3 for 1λ, S2~S3 for 2λ, S3 for 4λ, and none for 8λ):
  - A retarder with an even number of switches at 0° following it ==>the retardance will be added on the total delay; otherwise, subtracted.
  - The last retarder always add to the total delay.
- Subtraction of the two sets of data with either 0 or π phase shift gives the cosine components of the Fourier transformation, while the addition gives the zero-order.

FY'03 Accomplishment
- Testing with 3-stage Module (Continued)

- **Cosine and zero-order component measurement result**

  Zero-order not completely flat due to the use of only 3 stages

Output **S1S2S3S4Optical delays()Phaseshiftvoltage (V)**14545008-4-2-1=102.3920

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						π	
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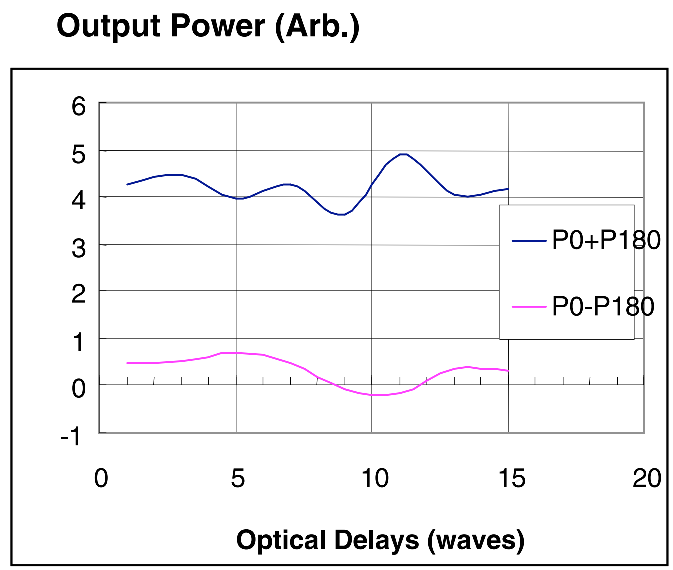

Measured zero-order (blue) and cosine (pink) components of the EO-IFTS

FY'03 Accomplishment
- Testing with 3-stage Module (Continued)

Phase Switch Scheme for obtain Sine components :

- By aligning $\lambda/4$ wave plate to 45°
- Rotate $\lambda/2$ wave plate (S4) so the output of two beams are either of $\pi/2$ phase shift (if S4 is at at 45°) or of $-\pi/2$ phase shift (if S4 is at 0°)
  - Switches S1~S3 all add a π phase shift to MOS output ==> total effective phase shift: π
  - The polarization status between two components depends only on $\lambda/2$ wave plate (S4)
- As in cosine case, each retarder experiences all its subsequent switch operations (i.e., S1~S3 for 1λ, S2~S3 for 2λ, S3for 4λ, and none for 8λ):
  - A retarder with an even number of switches at 0° following it ==>the retardance will be added on the total delay; otherwise, subtracted.
  - The last retarder always add to the total delay.
- Subtraction of the two sets of data with either 0 or π phase shift gives the sine components of the Fourier transformation, while the addition gives the zero-order.

FY'03 Accomplishment
- Testing with 3-stage Module (Continued)

- **Sine and zero-order components and measurement result:**

  Zero-order not completely flat due to the use of only 3 stages

OutputStat(S1S2S3S4Optical delays()Phaseshiftvoltage (V) 14545008-4-2-1=12.12045(
λ

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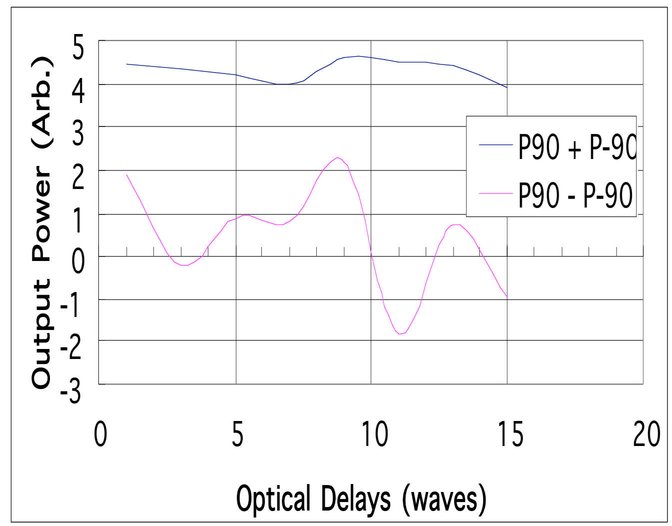
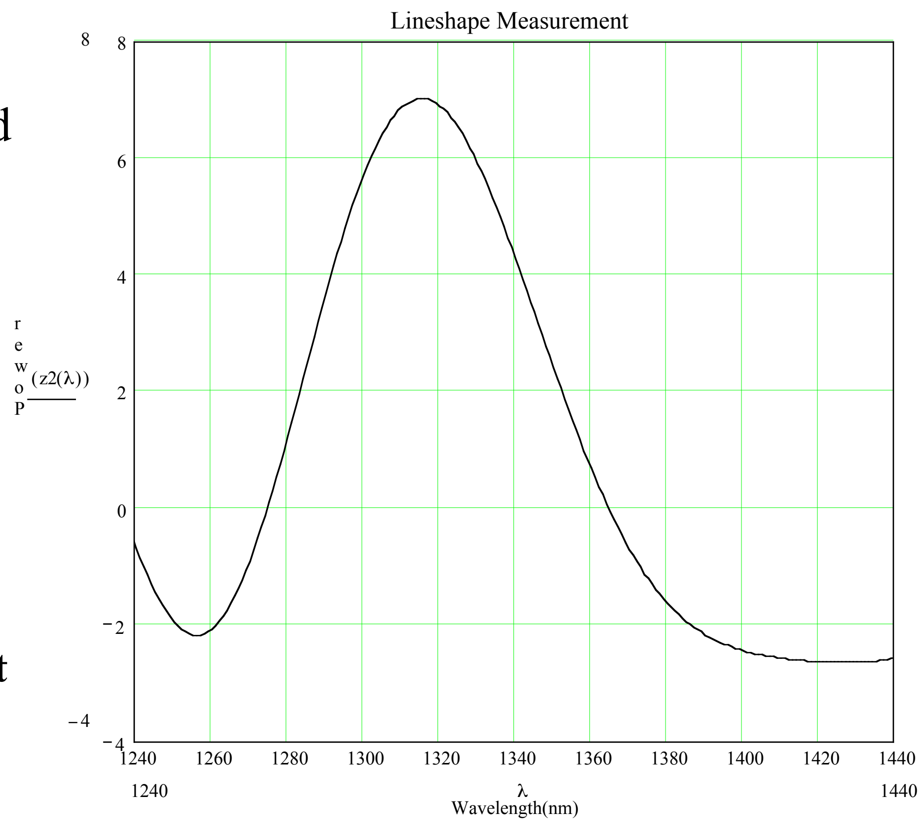


Measured zero-order (blue) and sine (pink) components of the EO-IFTS

FY‘03 Accomplishment
- *Spectrum Recovery from Measured Data*

- A preliminary algorithm for recover spectrum from measured data developed
- The dispersion effect of the quartz was incorporated
- Identified the 1310nm laser wavelength . The 3-stage FT spectrumeter resolution is about 145nm.
    - **The measurement result of the laser linewidth match that of the theoretical estimation.**



Investigation of high-birefringence, lightweight Phase Retarder Material

Materials	Birefringence Δn	Transmission Range	Thickness of 256 wave numbers at 1.5 μm
Quartz	0.0091 @633nm	0.20-2.3 μm	42.2 mm
Calcite	0.171 @633nm	0.21-2.3 μm	2.25 mm
YVO_4	0.205 @1300nm	0.40-5.0 μm	1.87 mm

- YVO_4 (Yttrium Vanadate) possesses all advantages in spectral transmission bandwidth, high birefringence, and thickness phase retarders.

Future Work

- Fabricate high-order passive retarders using YVO_4 materials for multiple-stage module and measure performance
- Optimize performance of achromatic switches by improving optical uniformity and flat spectral response.
- Build a compact 6- stage IR FTS optical head using compact packaging technology
- Optimize the spectrum recovery algorithm.
- Conduct benchmark tests of the IR FTS optical head for its combinatorial time delay performance and spectral response using laser.

Future Work

- Develop PC based switching circuitry and control HW/SW
- Integrate the entire E-O IFTS by combining an imaging optics (a mirror-lens), the multi-stage head, and a broadband IR photodetector, and I/O HW/SW
- Develop PC based switching circuitry and control HW/SW
- Conduct performance test including spectral data collection, perform recovering algorithm computation